CERTIFICATION PROCEDURES
FOR THE
THOR-FLX/HYBRID III RETROFIT VERSION 1.0

July, 2001

National Highway Traffic Safety Administration
Vehicle Research and Test Center

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Certification Procedure for the
Thor-FLX/Hybrid III Retrofit Version 1.0

July, 2001

I. Background

This document describes the procedures employed to certify the proper functionality of the National Highway Traffic Safety Administration (NHTSA) 5th percentile female advanced dummy lower leg, Thor-FLX/Hybrid III retrofit version 1.0 (Thor-FLX/HIIIr). The Thor-FLX/HIIIr is part of the NHTSA advanced dummy effort, Thor, and exhibits improved biofidelic response and greater instrumentation capabilities.

Similar to the 50th percentile male model, Thor-LX/HIIIr, the Thor-FLX/HIIIr is designed for Hybrid III retrofit use and attaches directly to the distal end of the Hybrid III 5th percentile female femur. The Thor-FLX/HIIIr consists of the Thor-FLX foot and ankle segments, the Thor-FLX tibia segment, Hybrid III knee housing, a modified Hybrid III knee flesh, molded side knee covers, and the Hybrid III ball bearing knee slider assembly.

Figure 1 below shows the Thor-FLX/HIIIr. The appropriate tibia flesh elements are not shown. Figure 2 is a schematic drawing that defines key elements and sub-assemblies of the leg. Instrumentation capabilities are presented in Figure 3. Further detail on the individual leg components and product assembly and disassembly can be found in the Thor-FLX/HIIIr Drawing Package and User's Manual.

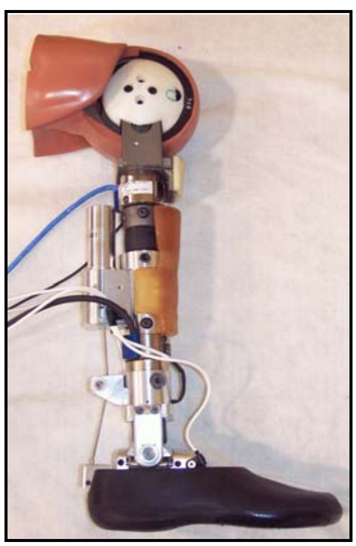

Figure 1. Thor-FLX/HIIIr
(tibia flesh removed)

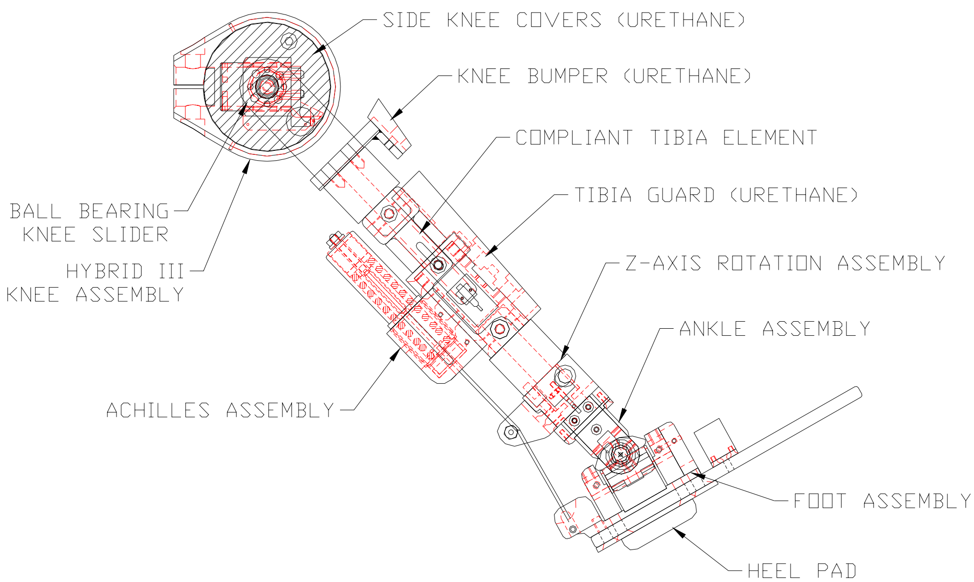

Figure 2. Thor-FLX/HIIIr schematic drawing with labeled key element and sub-assemblies

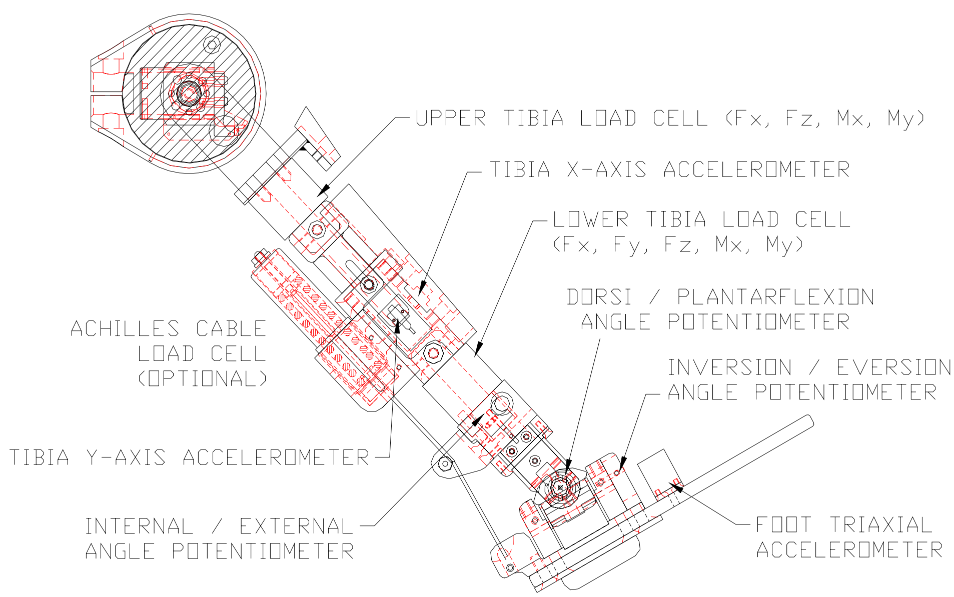

Figure 3. Thor-FLX/HIIIr schematic drawing defining instrumentation location and capabilities

II. Performance Requirements

The performance of the Thor-FLX/HIIIr is defined with two sets of criteria:

- mandatory certification requirements
- design reference guidelines

A certified Thor-FLX/HIIIr will pass all of the mandatory certification requirements shown below in Table 1. The design reference guidelines are used as an additional functionality check of the leg assembly. It is not necessary for leg certification that each leg meets every design reference guideline, however, all tests will be performed by the manufacturer and results will be released to the customer. The design reference guidelines for the Thor-FLX/HIIIr are listed in Appendix A.

A series of quasi-static and dynamic impact tests is used to certify the performance of the Thor-FLX/HIIIr. The inversion and eversion performance of the leg is validated by analysis of the torque-angle response from the quasi-static ankle motion tests. The dynamic dorsiflexion and Achilles tendon response are verified with a pendulum impact to the ball of the foot, while the axial compliance of the leg assembly is tested with a pendulum impact to the heel of the foot.

Table 1. Thor-FLX/HIIIr mandatory certification requirements

Quasi-Static Tests	Inversion & Eversion angles:	
	At 8 N·m	19.2 - 23.4°
	At 17 N·m	28.5 - 34.9°
Dynamic Ball of Foot Impact	Peak Lower Tibia Compressive Force	2294 - 2804 N
	Peak Ankle Resistive Moment	39.6 - 48.4 Nm
Dynamic Heel of Foot Impact	Peak Lower Tibia Compressive Force	1987 - 2429 N

The Thor-FLX/HIIIr knee assembly is examined with the standard calibration procedure in the Code of Federal Regulations Part 572, Subpart O. The performance of the ball bearing knee slider is verified with the calibration test in the SAE Engineering Aid 25.

The sign convention utilized for the test procedures follows the standardized SAE crash test dummy coordinate system.

The test procedures and target response values for the mandatory certification requirements and the design reference guidelines are explained in detail in this document to provide users the capability to repeat tests and verify consistent performance.

III. Quasi-Static Ankle Motion Tests

(A) The quasi-static ankle motion tests were designed to examine the performance of the ankle joint in the inversion and eversion directions. Inversion is defined as rotation about the foot anterior/posterior axis toward the midline of the body, while eversion is defined as rotation about the foot anterior/posterior axis away from the midline of the body. The response of the ankle rubber bumpers is examined with this test procedure. Similar tests are used as design reference guidelines for dorsiflexion with the Achilles tendon, dorsiflexion without the Achilles tendon, and plantarflexion. The procedure and corridors for examining the design reference guidelines are shown in Appendix A.

(B) The test fixtures employed in the quasi-static ankle motion tests can be determined by the test lab and are subject to variation. The experimental setup used at the NHTSA Vehicle Research and Test Center (VRTC) is explained in detail along with accompanying figures and sample test data in Appendix B.

(C) The Thor-FLX/HIIIr parts required for the quasi-static tests are:

- Tibia, ankle, and foot assemblies (Figure 2)
- Dorsi/plantarflexion and inversion/eversion angle potentiometers (Figure 3)

(D) **Test Procedure - Inversion/Eversion Quasi-Static Tests**

1. Inspect the ankle rubber bumpers for uneven wear, tears, or other damage. Check for smooth rotation of the ankle about the X, Y, and Z-axes.

2. Soak the ankle, foot, and tibia assemblies in a controlled environment at a temperature between 69° and 72°F for at least four hours prior to testing. The test environment should have the same temperature as the soak environment.

3. The potentiometer channels should be set according to calibration values provided by the manufacturer. Verify the accuracy of the ankle potentiometers at zero position with the ankle rotary potentiometer zeroing fixture, as described in the Thor-FLX/HIIIr User's Manual.

4. Rigidly mount the tibia and align the foot at zero position (Figure 4). Detach the Achilles cable during the inversion and eversion tests (see Thor-FLX/HIIIr User's Manual). The ankle should remain at 0° dorsiflexion and plantarflexion during the inversion and eversion test, and pivot only about the X-axis. Additionally, rotation about the Z-axis is

undesirable during testing and should be prevented. If necessary, an external bracket can be used at the ankle joint to maintain 0^{o} dorsiflexion and plantarflexion. One possible bracket design is depicted below in Figure 5. An engineering drawing for this design is shown in Appendix B, Figure B-10.

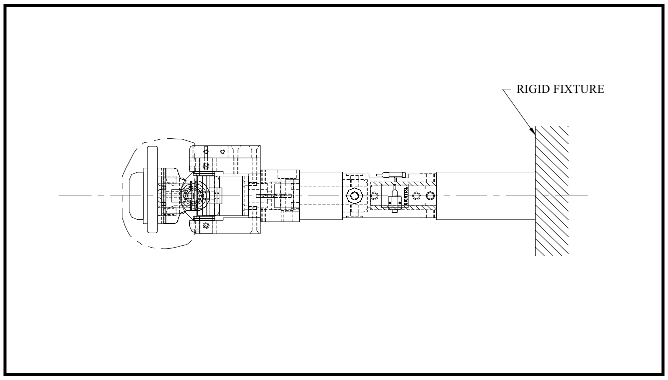

Figure 4. Thor-FLX/HIIIr zero position - initial starting position for quasi-static inversion and eversion tests. (0^{o} dorsiflexion, plantarflexion, inversion, and eversion, 0^{o} rotation about the Z-axis)

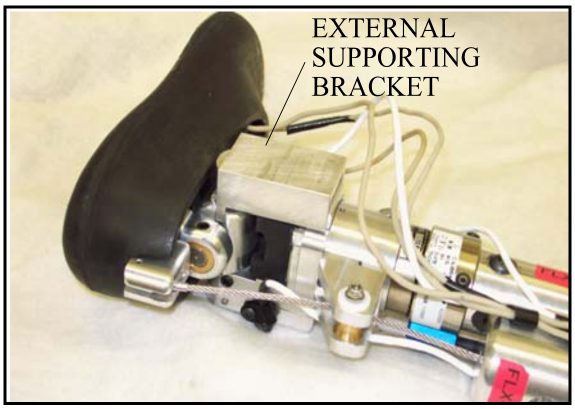

Figure 5. Thor-FLX/HIIIr with external supporting bracket to maintain 0^{o} dorsiflexion and plantarflexion

5. Apply a force to rotate the foot about the X-axis in the inversion or eversion direction at a rate of 1 - 2^{o}/second from zero position until a torque of at least 17 Nm is reached. (Note: Do not exceed 38^{o} inversion or eversion as this angle is near the joint mechanical limit.)

6. The applied force and ankle potentiometer channels should be continuously recorded during the test procedure.

7. Calculate the torque at the ankle joint. Sample calculations for the VRTC test setup are shown in Appendix B.

(E) **Performance Specifications - Inversion/Eversion quasi-static tests**

1. Plot the torque-angle response in both the inversion and eversion directions. Figures 6 and 7 show torque-angle plots for inversion and eversion, respectively, of a typical Thor-FLX/HIIIr assembly. Biofidelic specifications are also shown.

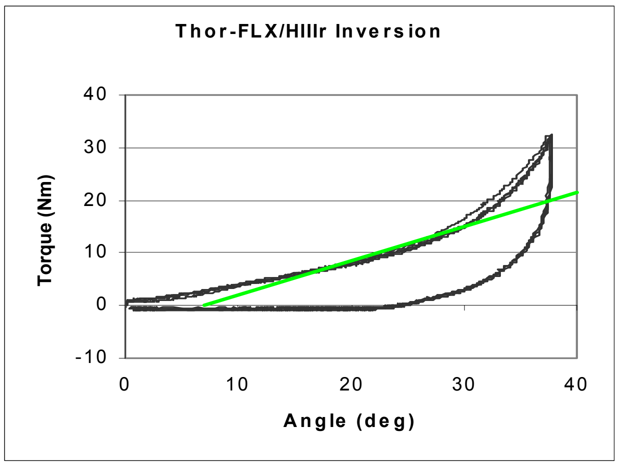

Figure 6. Thor-FLX/HIIIr torque-angle response for quasi-static inversion test with biofidelic specification (four tests shown)

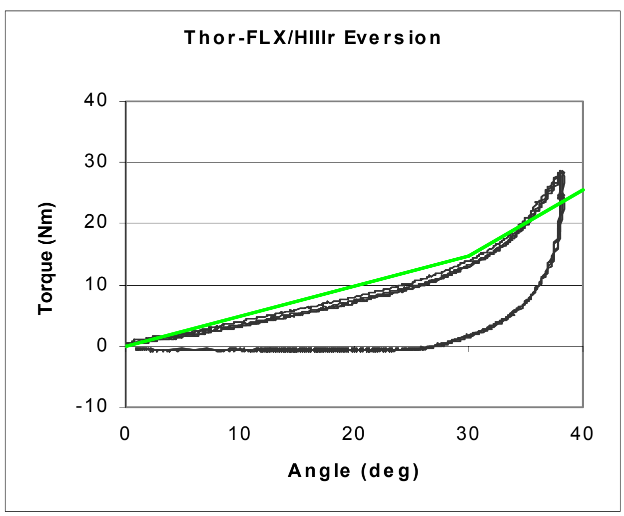

Figure 7. Thor-FLX/HIIIr torque-angle response for quasi-static eversion test with biofidelic specification (four tests shown)

2. The angle at which the following torque values are measured should be within the corresponding ranges:

Inversion/Eversion	at 8 Nm:	19.2 - 23.4^{o}
	at 17 Nm:	28.5 - 34.9^{o}

The design reference guidelines for the quasi-static dorsiflexion with the Achilles tendon, dorsiflexion without the Achilles tendon, and plantarflexion tests are listed in Appendix A.

IV. Dynamic Impact Tests

(A) The dynamic performance of the Thor-FLX/HIIIr is examined with two pendulum tests, one each to the ball of the foot and the heel of the foot. The ball of foot impact test examines the dynamic dorsiflexion response, including the Achilles tendon and the dorsiflexion rubber bumpers, while the heel impact test validates the compliance of the tibia compressive element and the heel pad.

(B) The Thor-FLX/HIIIr components required for the dynamic impact tests are (Figure 2 and Figure 3):

- Foot, ankle, and tibia assemblies
- Lower tibia load cell
- Upper tibia load cell (heel of foot test only)
- X, Y, and Z-axis ankle rotary potentiometers

(C) The required fixtures for this test are:

- NHTSA Dynamic Impactor-5F (FLX-9000-013, Figure 8)
- Tibia Mounting Fixture-5F (FLX-9000-004, Figure C-4, ball of foot test only)

(D) The impactor used for the dynamic strikes to the ball and heel of the foot is shown in Figure 8. The combined mass of the impactor face, ballast, and 1/3 of the supporting tube is 3.03 kg. Because the densities and weights of some materials may vary, slight adjustment of the dimensions may be needed to achieve the same mass. The mass of the NHTSA Dynamic Impactor-5F (FLX-9000-013) has been scaled from the pendulum impactor used for the certification of the Thor-Lx/HIIIr 50^{th} percentile male. The size of the impactor ballast was reduced for the NHTSA Dynamic Impactor-5F to achieve this lesser mass. The pendulum arm (TLX-9000-007) and the impactor face (TLX-9000-006) are the same as that used with the Thor-Lx/HIIIr 50^{th} percentile male certification procedure. Detailed drawings of the individual pendulum components are shown in Appendix C.

(E) The pendulum arm is mounted to a rigid shaft which is pivoted on low friction ball bearings. The supporting structure for the NHTSA Dynamic Impactor-5F is determined by the test facility.

(F) The data acquisition system must conform to requirements of the latest revision of SAE Recommended Practice J211. Data channels should be filtered using Channel Class 600 phaseless filters.

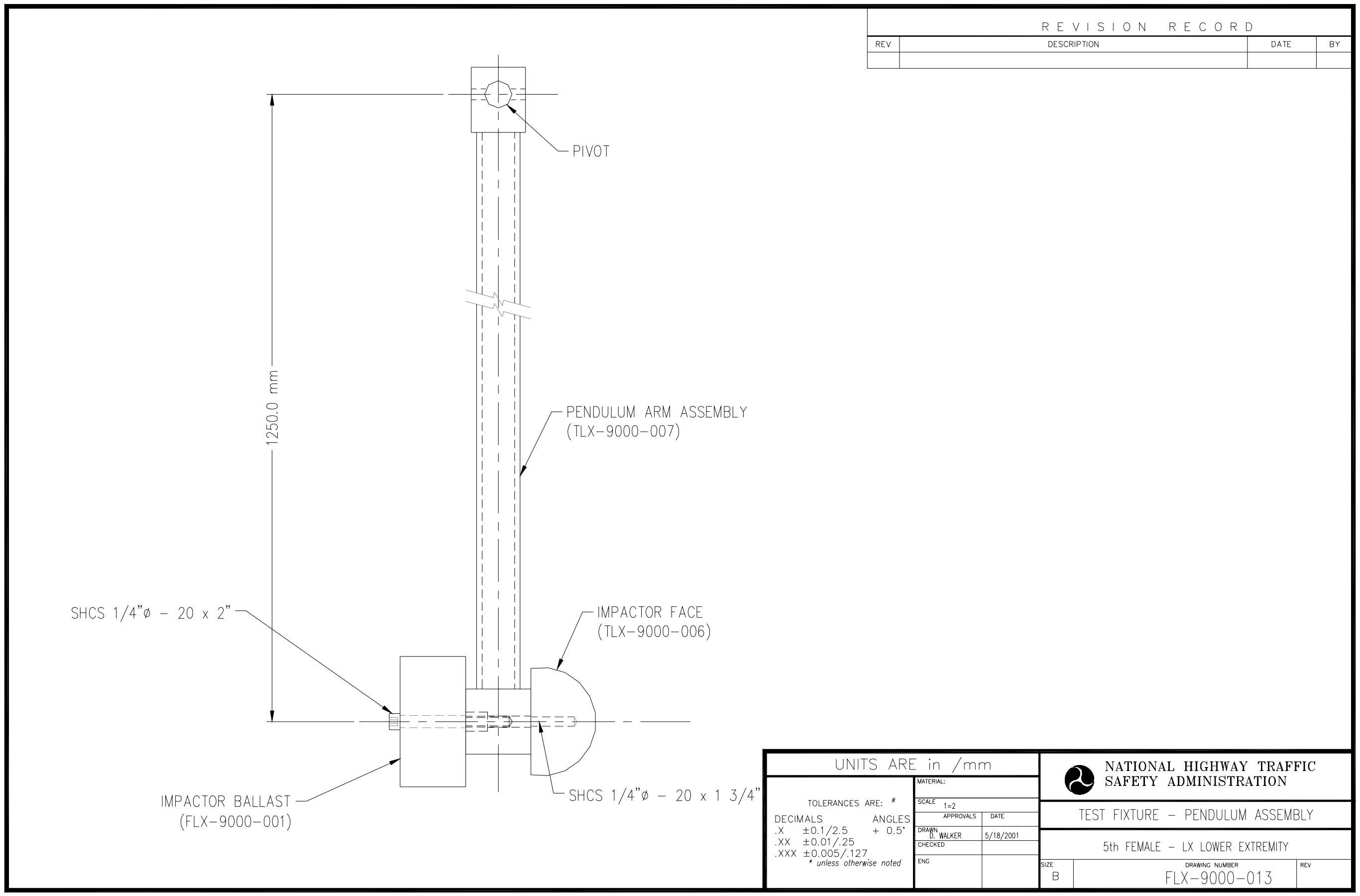

Figure 8. NHTSA Dynamic Impactor-5F for Thor-FLX/HIIIr

(G) **Test Procedure - Ball of foot impact**

This test consists of a dynamic impact to the ball of the foot. The leg is held rigidly with the tibia horizontal. A drawing of the test setup is shown in Figure 9.

1. Inspect the ankle rubber bumpers for tears, permanent deformations, or separation from the supporting brackets. Inspect the foot flesh for wear and cracks.

2. Soak the ankle, foot, and tibia assemblies in a controlled environment at a temperature between 69 and 72°F for at least four hours prior to testing. The test environment should be the same temperature as the soak environment.

3. Remove the tibia compliant bushing assembly and mount the leg to the Tibia Mounting Fixture (FLX-9000-004, Figure C-4) at the proximal end of the lower tibia tube with the toe pointing upward, as shown in Figure 9. The test fixture must be rigidly secured so that it does not move during impact. The certification corridors were developed with the tibia compliant bushing assembly removed, and testing with this assembly attached to the leg may alter performance and is not desirable. The behavior of the tibia compliant bushing assembly is examined with the heel of the foot impact tests.

4. Verify the proper attachment of the Achilles cable and the correct adjustment of the spring cable tension following the procedure described in the Thor-FLX/HIIIr User's Manual.

5. Verify the accuracy of the ankle rotary potentiometers with the rotary potentiometer zeroing fixture (See Thor-FLX/HIIIr User's Manual.)

6. Position the foot at $15 \pm 1^{\circ}$ plantarflexion, $0 \pm 1^{\circ}$ inversion and eversion, and $0 \pm 1^{\circ}$ rotation about the Z-axis. This is the Thor-FLX/HIIIr neutral position. Readjust the foot to this position if necessary between impacts.

7. The longitudinal centerline of the pendulum should be vertical at impact, and the point of impact is 92.5 mm (3.64 in) above the tibia centerline

8. Wait at least 30 minutes between successive impacts to the same foot.

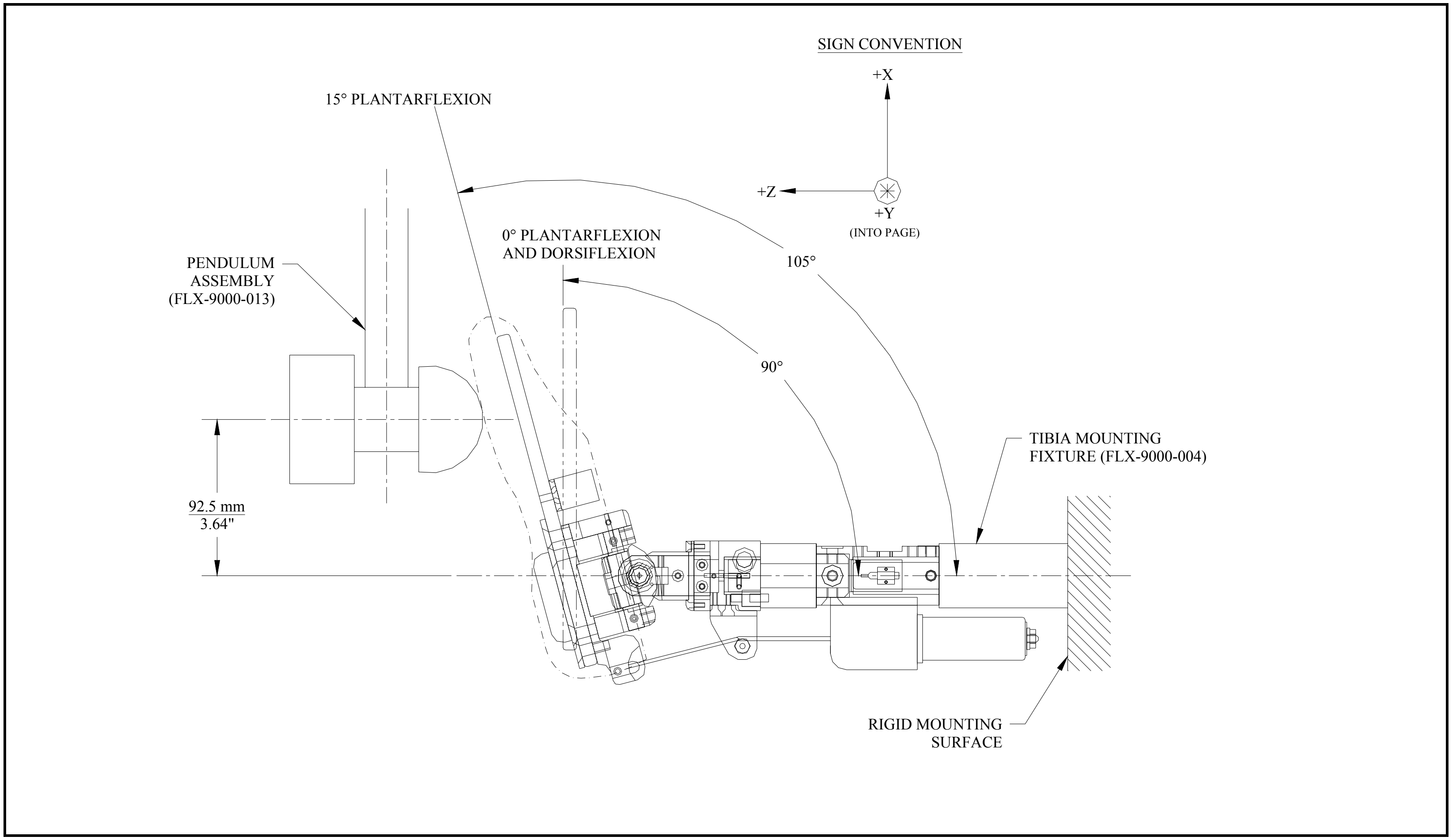

Figure 9. Thor-FLX/HIIIr dynamic ball of foot impact test setup

(H) **Performance Specifications - Ball of Foot Impact**

1. Release the pendulum and allow it to fall freely from a height to achieve an impact velocity of 5.0 ± 0.1 m/s (16.4 ± 0.3 ft/s)

2. Time-zero is defined as the time of initial contact between the pendulum face and the ball of the foot. All channels, except the Y-axis rotary potentiometer, should be zero at this time.

3. Record the following data channels:
   - Lower tibia load cell - Fx, Fz, My
   - Y-axis rotary potentiometer

4. Compute the ankle resistive moment by My - (a * Fx) where:

   My = Moment about the Y-axis measured by lower tibia load cell
   Fx = Force in X-direction measured by lower tibia load cell
   a = distance from the center of the lower tibia load cell to the dorsiflexion ankle joint (for Thor-FLX/HIIIr, a = 0.0884m)

5. The peak lower tibia compressive force (Fz) should be between 2294 - 2804 N. The peak ankle resistive moment should be within 39.6 - 48.4 Nm. The design reference guidelines for the ball of foot impact test examine the performance at lower dorsiflexion angles and are shown in Appendix A.

(I) **Test Procedure - Heel of foot impact test**

This test consists of a pendulum impact to the heel of the foot. The leg is held rigidly with the tibia horizontal (Figure 10).

1. Inspect the foot flesh, heel pad, and tibia compliant element for cracks, tears, or permanent deformations. Replace if damage is excessive.

2. Soak the ankle, foot, and tibia assemblies in a controlled environment at a temperature between 69° and 72°F for at least four hours prior to testing. The test environment should be the same as the soak environment.

3. Verify the accuracy of the ankle rotary potentiometers using the Thor-FLX/HIIIr zeroing calibration fixture. (See Thor-FLX/HIIIr User's Manual)

4. Remove the knee clevis and rigidly mount the tibia to the test fixture at the proximal end of the upper tibia load cell with the toe pointing upward, as shown in Figure 10. The test fixture must be rigidly secured so that it does not move during impact. Verify that the Achilles tendon cable is properly attached (See Thor-FLX/HIIIr User's Manual).

5. Position the foot at 0 ± 1° dorsiflexion, plantarflexion, inversion, eversion and rotation about the Z-axis. If necessary, an external supporting bracket may be used at the ankle joint to keep the foot in this position during testing. An example of a bracket design to hold the foot at 0° dorsiflexion and plantarflexion is shown above in Figure 5. An engineering drawing of the bracket is illustrated in Appendix B, Figure B-10.

6. The longitudinal centerline of the pendulum arm should be vertical at impact, and the impact point should be in line with the tibia centerline.

7. Wait at least 30 minutes between successive impacts to the same foot.

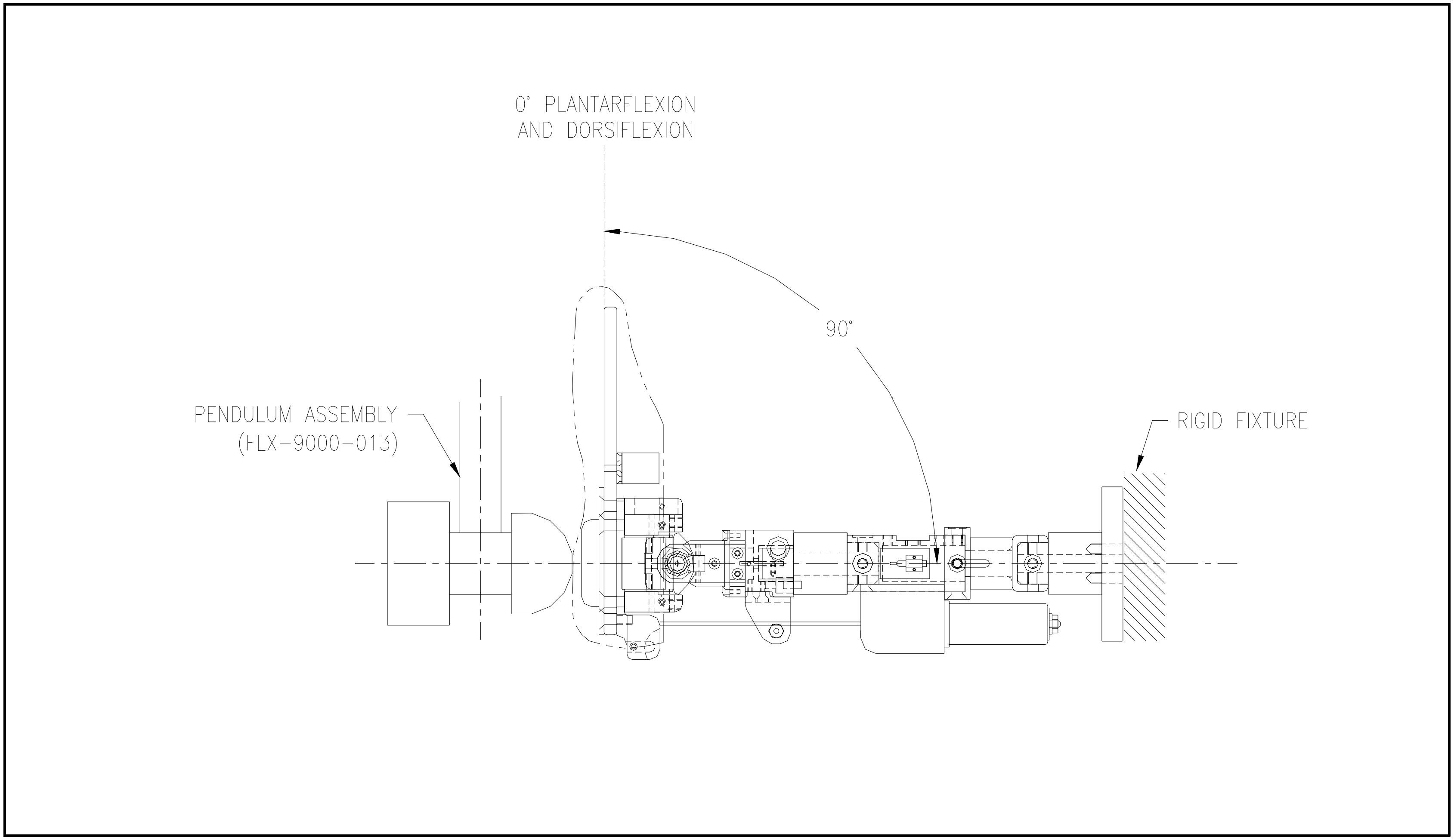

Figure 10. Thor-FLX/HIIIr heel of foot impact test setup

(J) **Performance Specifications - Heel of Foot Impact**

1. Release the pendulum and allow it to fall freely from a height to achieve an initial impact velocity of 4.0 ± 0.1 m/s (13.1 ± 0.3 ft/s).

2. Time-zero is defined as the time of initial contact between the pendulum face and the foot flesh. Instrumentation channels should be zero at this time.

3. Record the compressive force (Fz) measured by the lower tibia load cell during the test.

4. The peak compressive force (Fz) measured by the lower tibia load cell should be within the range of 1987 - 2429 N.

APPENDIX A

Design Reference Guidelines

(A) The design reference guidelines for the Thor-FLX/HIIIr are listed below in Table A-1, along with the document containing the test description. These criteria are examined in addition to the mandatory certification requirements listed in Table 1. It is not necessary for certification of the leg assemblies that all design reference guidelines are met. However, all manufacturer test data from both the mandatory certification requirements and the design reference guidelines will be released to the customer with the hardware.

Table A-1. Design reference guidelines for Thor-FLX/HIIIr

Described in this appendix:	Quasi-Static Tests	Torque	Angle
	Dorsiflexion with Achilles tendon	25 Nm	18.7 - 22.9°
		55 Nm	33.2 - 40.6°
	Dorsiflexion without Achilles tendon	9 Nm	20.2 - 24.6°
		25 Nm	35.0 - 42.8°
	Plantarflexion	4 Nm	28.9 - 35.3°
		12.5 Nm	42.3 - 51.7°
	Dynamic Ball of Foot Impact Test		
	Lower tibia My peak between -15° - 0°	60.0 - 73.4 Nm	
	Lower tibia My peak between 0° - 15°	44.1 - 53.9 Nm	
In Drawing Package:	Tibia puck axial static procedure (T2LLM412)		
	Heel pad axial static procedure (T2FTM214)		
	Achilles spring rate axial static procedure (T2LLM300)		
	Achilles spring force-deflection axial static procedure (T2LLM301)		
	Internal/external rotation moment-angle static procedure (T2LXM001)		
	Rotary potentiometer 10-point calibration procedure (T2AKM000)		
In User's Manual:	Rotary potentiometer zeroing procedure		

(B) Quasi-Static Ankle Motion Tests

The design reference guidelines for the quasi-static tests examine the range of motion and resistance of the ankle bumpers in the dorsiflexion with Achilles tendon, dorsiflexion without the Achilles tendon, and plantarflexion directions. The test procedure follows that described in Section III, and steps 4 and 5 are adjusted for the dorsiflexion and plantarflexion tests to read as follows:

4. Rigidly mount the tibia and allow the foot to rest at neutral position (15° plantarflexion, 0° inversion and eversion, 0° rotation about the Z-axis). This is the initial starting position for the dorsiflexion and plantarflexion tests. The Achilles tendon should be attached only for the dorsiflexion with Achilles tendon test.

5. Apply a force to rotate the foot about the Y-axis in the dorsiflexion or plantarflexion direction at a rate of 1 - 2°/second from neutral position until the following minimum torque values are attained for each test:

Dorsiflexion with Achilles tendon:	55 Nm
Dorsiflexion without Achilles tendon:	25 Nm
Plantarflexion:	12.5 Nm.

(Note: Do not exceed 42° dorsiflexion or 55° plantarflexion to avoid damage as these angles are near the joint mechanical limit.)

The design reference guidelines for the Thor-FLX/HIIIr quasi-static tests are shown above in Table A-1.

(C) Ball of Foot Impact Test

The design reference guidelines further analyze the ball of foot impact test described in Section IV. The dynamic dorsiflexion response is examined at lower angles as follows:

1. Plot the moment about the Y-axis measured by the lower tibia load cell against the dorsiflexion angle.

2. The peak moment about the Y-axis measured by the lower tibia load cell between -15 - 0° dorsiflexion should be within 60.0 - 73.4 Nm.

3. The peak moment about the Y-axis measured by the lower tibia load cell between 0 - 15° dorsiflexion should be between 44.1 - 53.9 Nm.

APPENDIX B

VRTC Quasi-Static Ankle Motion Test
Setup and Fixtures

This appendix describes the experimental test setup used for the quasi-static ankle motion tests at VRTC. This description is meant to be an example; it is not necessary to replicate this setup to perform the quasi-static ankle motion tests. Section III explains the setup and requirements necessary for the leg assembly to be certified.

(A) The equipment and fixtures utilized in this test are:

- Universal testing machine
- Rigid fixture to horizontally mount Thor-FLX/HIIIr
- Ankle moment arm (FLX-9000-014, Figure B-8)
- Cable Attachment Bracket (TLX-9000-012, Figure B-9)

(B) The data acquisition system, including transducers, should conform to the latest revision of the SAE Recommended Practice J211.

(C) Test Procedure:

1. Remove the foot flesh and attach the Ankle Moment Arm (FLX-9000-014, Figure B-8) to the bottom of the sole plate (T2FTM010) with four 1/4" - 20 x 1-1/4" flat head cap screws. The length of the moment arm for this fixture is 254 mm (10 in) for both the dorsiflexion/plantarflexion and inversion/eversion joints.

2. Rigidly and horizontally mount the tibia to a secure fixture and align the leg as follows:

Dorsiflexion:	15^{o} plantarflexion, 0^{o} inversion and eversion, 0^{o} rotation about the Z-axis (Figure B-1)
Plantarflexion:	15^{o} plantarflexion, 0^{o} inversion and eversion, 0^{o} rotation about the Z-axis (Figure B-2)
Inversion/Eversion:	0^{o} dorsiflexion, plantarflexion, inversion, and eversion, 0^{o} rotation about the Z-axis (Figure B-3)

3. Attach the cable attachment bracket (TLX-9000-012, Figure B-9) to the ankle moment arm (FLX-9000-014, Figure B-8) and secure the looped end of the steel cable to the universal testing machine. The length of the cable from pin-to-pin is 559 mm (22 in).

   The pulling cable should be perpendicular to the ankle moment arm when the ankle is at 0^{o} dorsiflexion/plantarflexion and 0^{o} inversion/eversion, but will not remain perpendicular during the test. The following variables are defined and used to calculate the torque at the ankle joint during the test procedure:

ϕ	= angle between pulling cable and vertical
θ	= rotation angle at ankle pivot
l	= length of cable assembly
a	= length of moment arm
P	= pulling force on cable

The variables are illustrated in Figures B-1 - B-4.

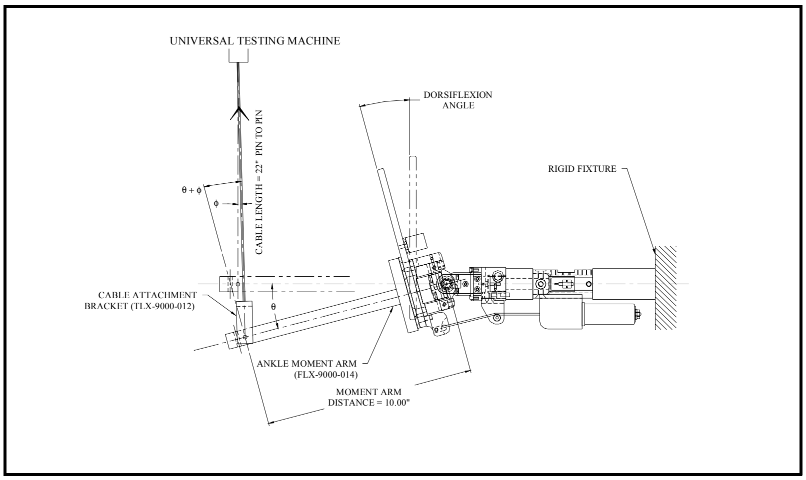

Figure B-1. Thor-FLX/HIIIr quasi-static dorsiflexion test setup

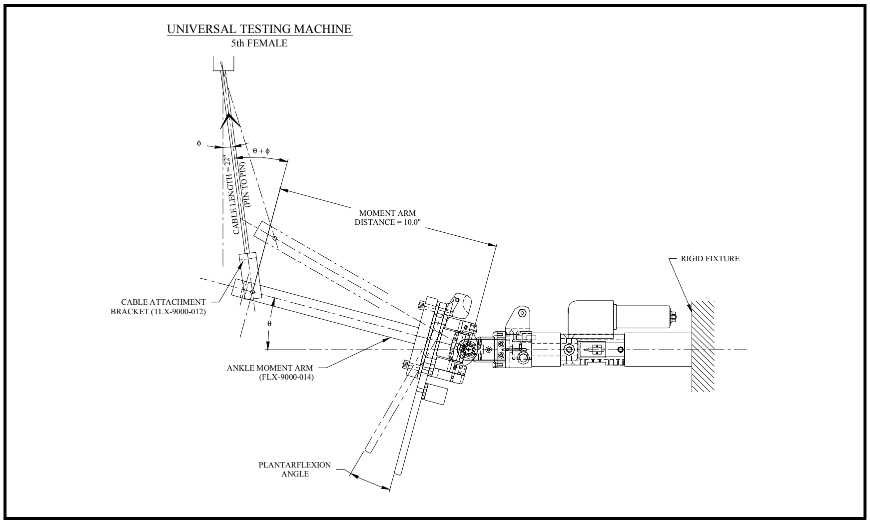

Figure B-2. Thor-FLX/HIIIr quasi-static plantarflexion test setup

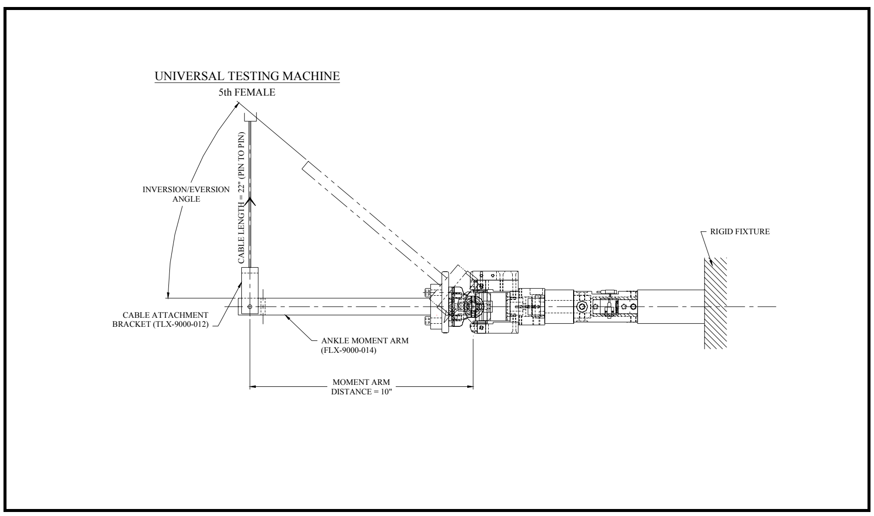

Figure B-3. Thor-FLX/HIIIr quasi-static inversion/eversion test setup

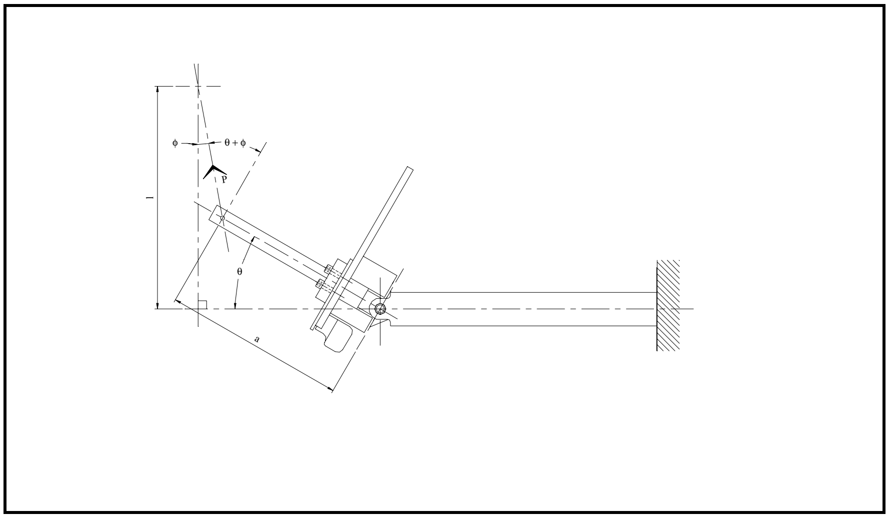

Figure B-4. Geometry setup for VRTC quasi-static tests

The torque about the ankle joint is determined as follows:

First, defining ϕ :

$$\phi = \sin^{-1}\left(\frac{a - a\cos\theta}{l}\right) \qquad (1)$$

or:

$$\phi = \sin^{-1}\left(\frac{a - a\cos\theta}{l}\right) \qquad (2)$$

The torque about the ankle joint can then be calculated by:

$$Torque(N \cdot m) = P \cdot a\cos(\theta + \phi) \qquad (3)$$

In the VRTC test setup, a = 254 mm (10 in) and l = 559 mm (22 in).

4. Verify the accuracy of the ankle potentiometers using the rotary potentiometer calibration fixture. (See Thor-FLX/HIIIr User's Manual)

5. From the initial starting positions described above in step 2, apply a force to rotate the ankle in the desired direction of motion at a rate of 1 - 2°/second using a moment arm distance of 254 mm (10 in) until the

following minimum torque values are obtained:

Dorsiflexion with Achilles tendon:	55 Nm
Dorsiflexion without Achilles tendon:	25 Nm
Plantarflexion:	12.5 Nm
Inversion/Eversion:	17 Nm

The Achilles tendon should be attached for only the dorsiflexion with Achilles test.

(Note: Do not exceed 42º dorsiflexion, 55º plantarflexion or 38º inversion or eversion to avoid damage.)

6. Record the following data channels:
   - X rotary potentiometer (inversion/eversion tests)
   - Y rotary potentiometer (dorsiflexion/plantarflexion tests)
   - Applied force

7. Calculate the ankle torque as described above in step 3.

(D) Performance Specifications

1. Sample Thor-FLX/HIIIr torque-angle plots for the dorsiflexion with and without Achilles tendon and plantarflexion tests are shown below in Figures B-5 - B-7.

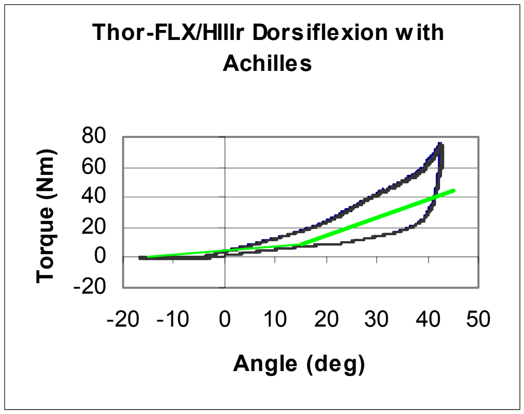

Figure B-5. Thor-FLX/HIIIr dorsiflexion with Achilles torque-angle response with biofidelic specification (four tests shown)

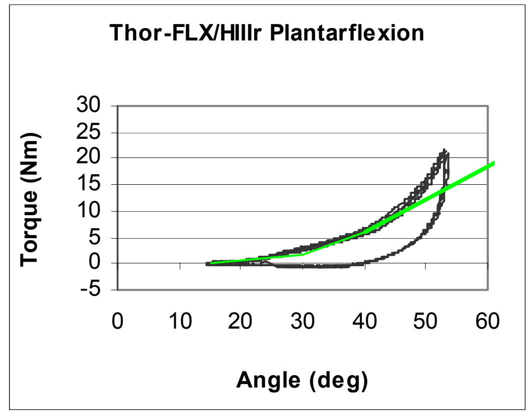

Figure B-7. Thor-FLX/HIIIr plantarflexion torque-angle response with biofidelic specification (four tests shown)

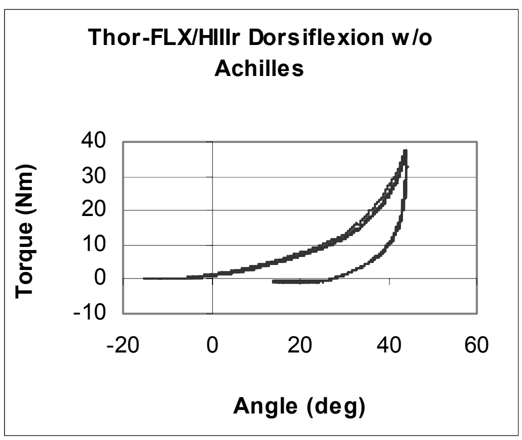

Figure B-6. Thor-FLX/HIIIr dorsiflexion without Achilles tendon torque-angle response (four tests shown)

The plots measured for the quasi-static inversion and eversion tests are shown in Figures 6 and 7 in the body of this document.

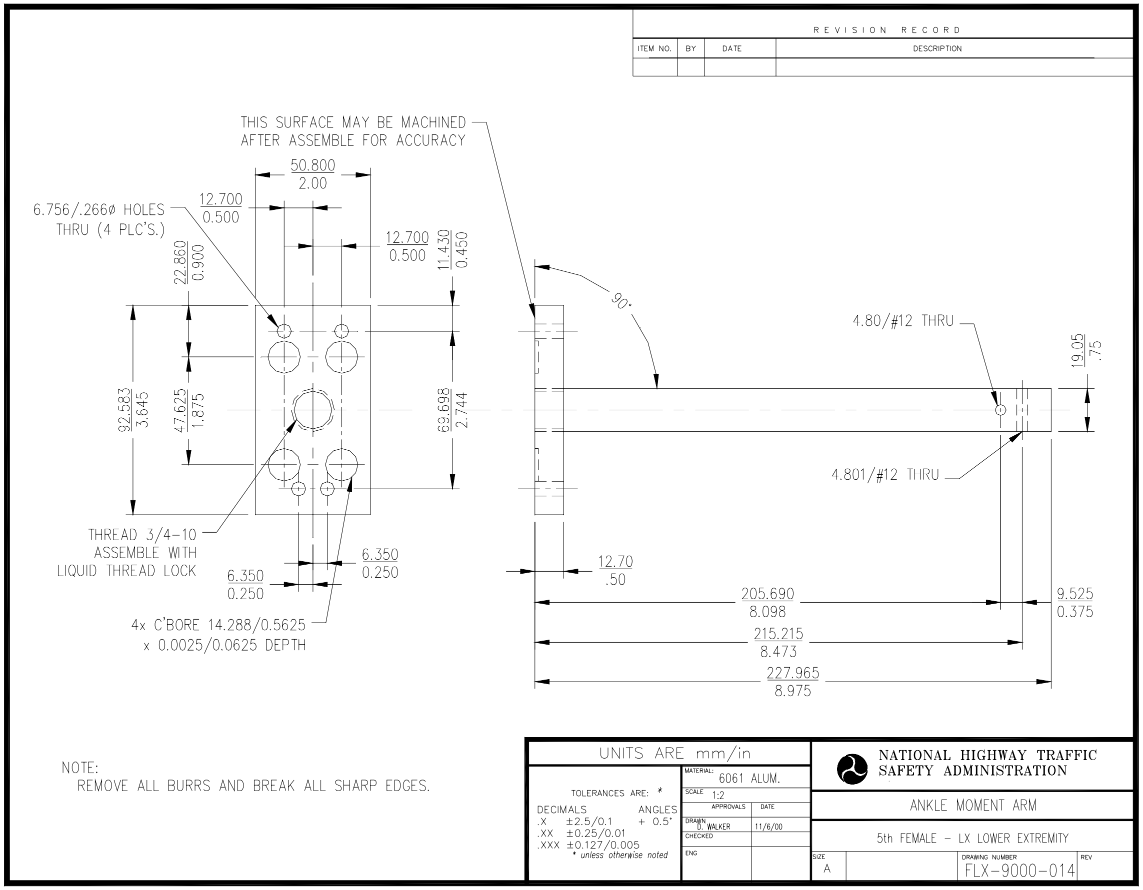

Figure B-8. Thor-FLX/HIIIr ankle moment arm

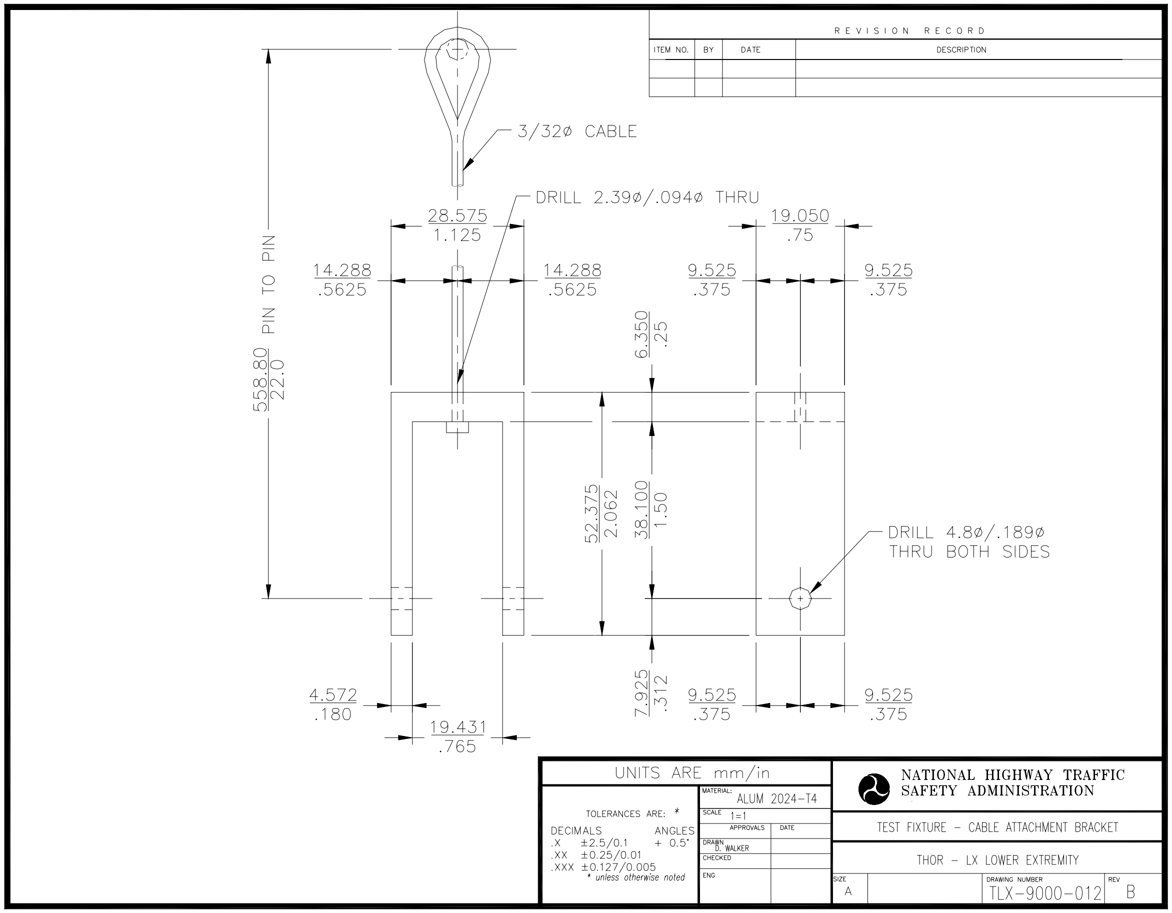

Figure B-9. Cable attachment bracket

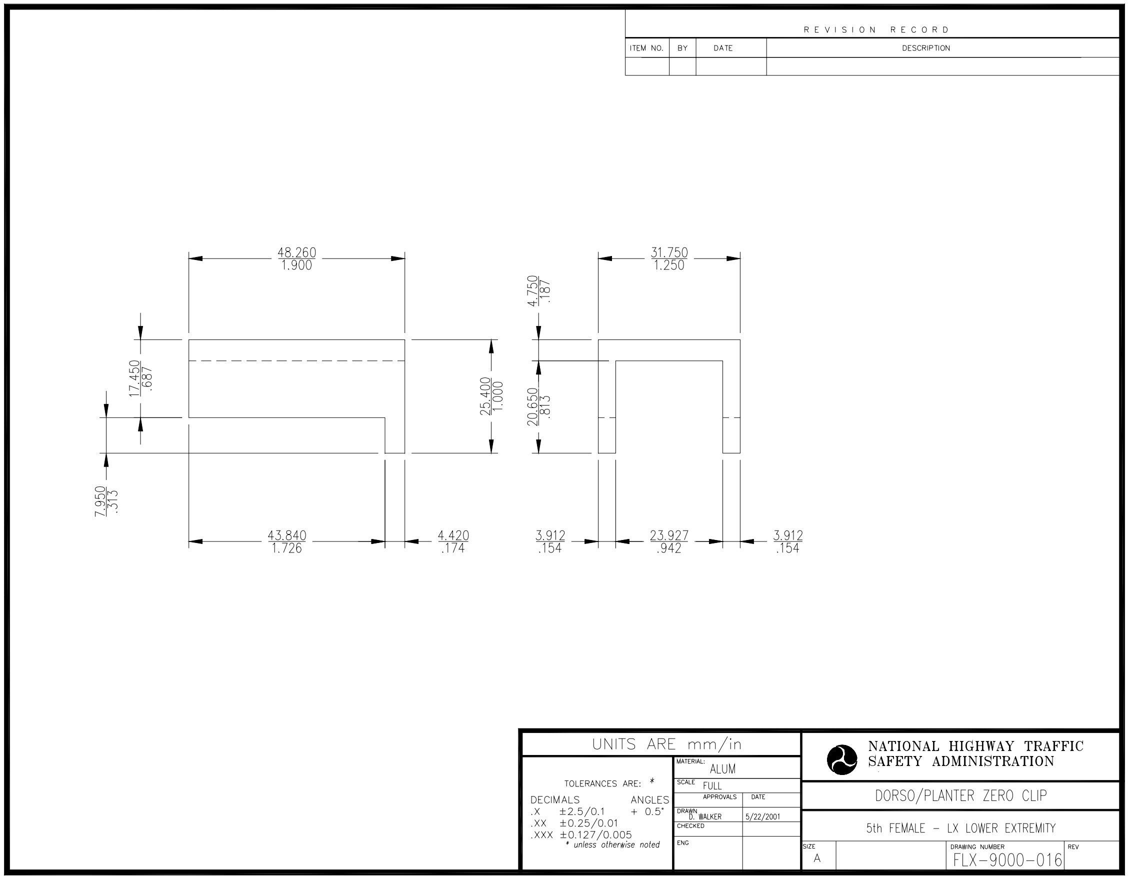

Figure B-10. Thor-FLX/HIIIr dorsiflexion/plantarflexion 0º bracket

Appendix C

Dynamic Test Fixtures

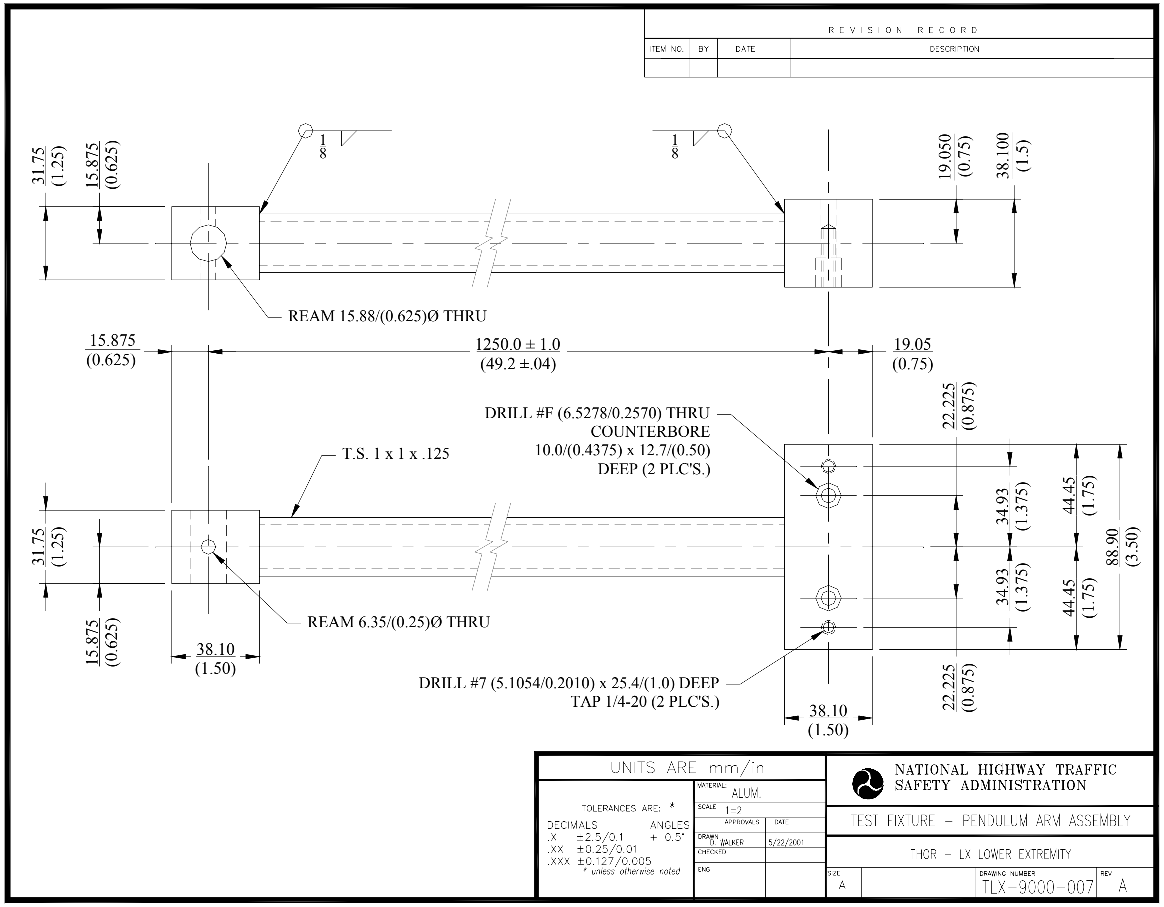

Figure C-1. Pendulum arm

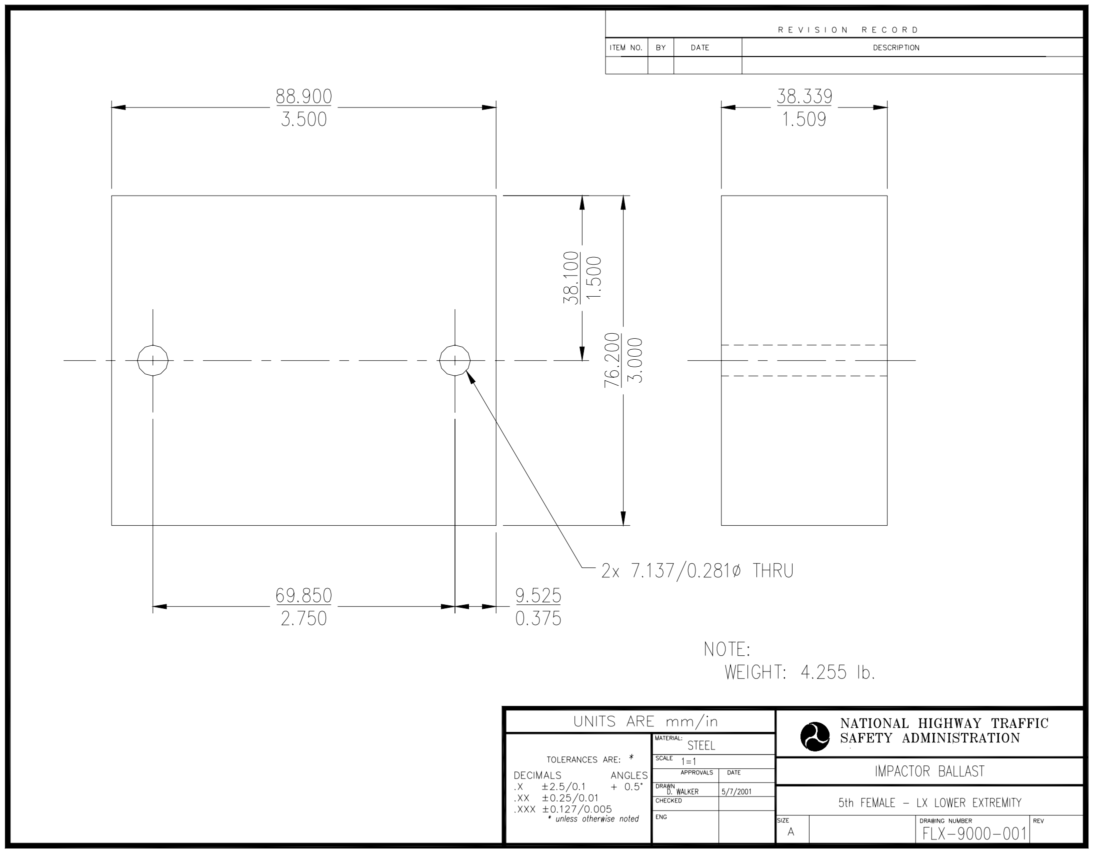

Figure C-2. Pendulum impactor ballast for Thor-FLX/HIIIr dynamic impacts

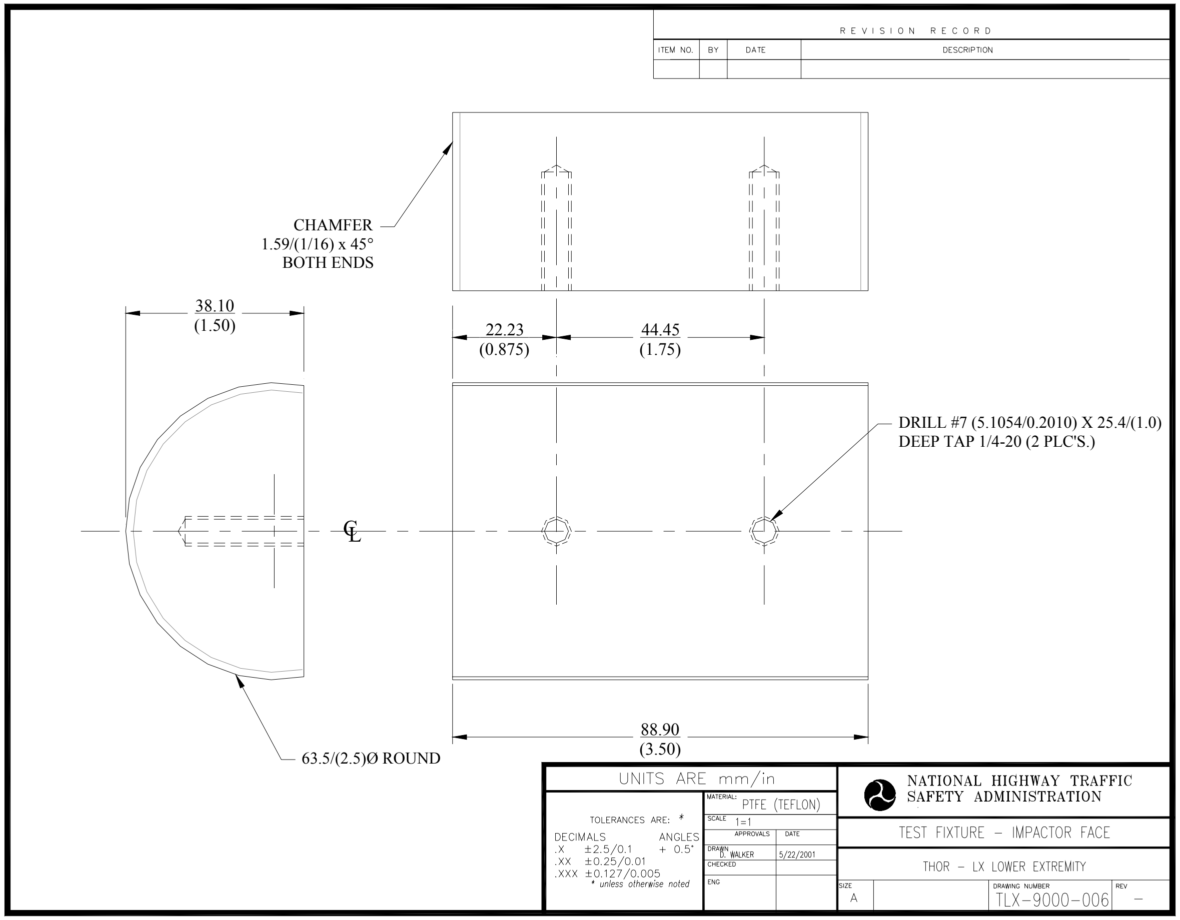

Figure C-3. Pendulum impactor face

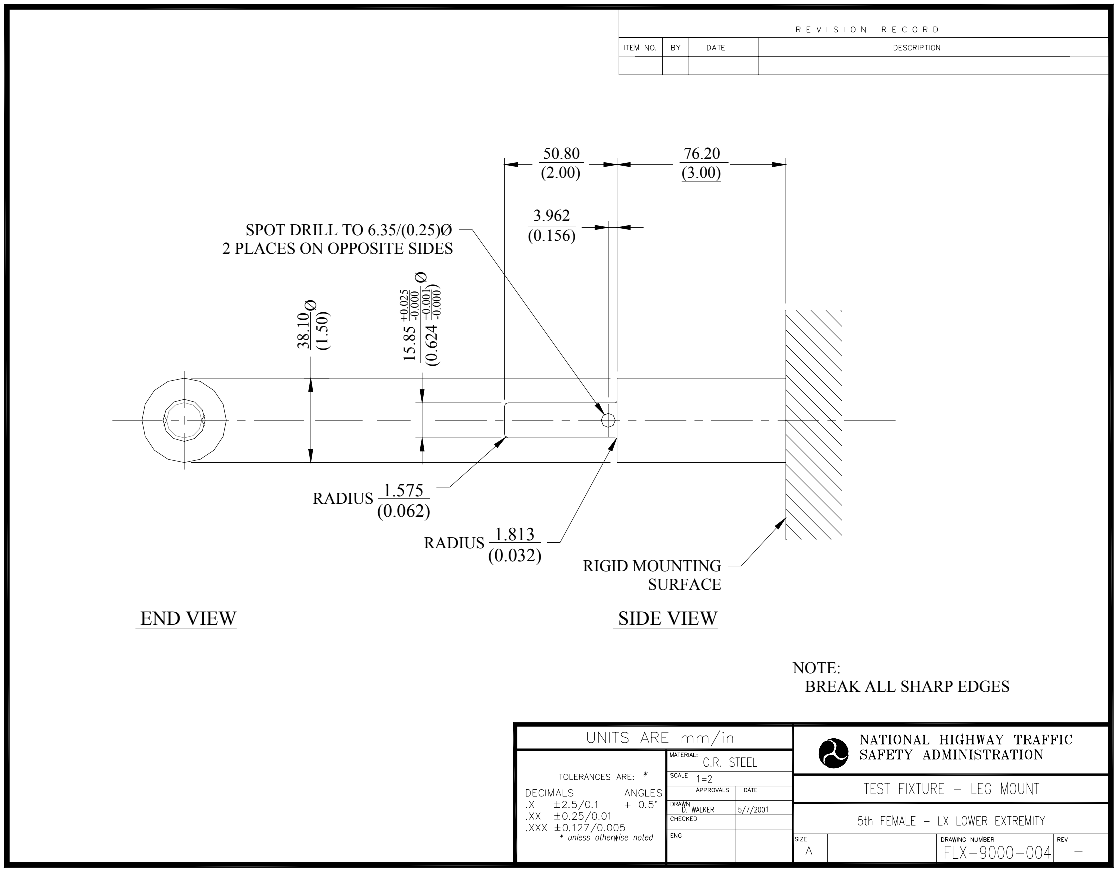

Figure C-4. Thor-FLX/HIIIr tibia mounting fixture for dynamic ball of foot impact test